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Natt et al.

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(54) **METHOD FOR OPERATING AN ILLUMINATION SYSTEM OF A MICROLITHOGRAPHIC PROJECTION EXPOSURE APPARATUS**

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(52) **U.S. Cl.**
CPC ***G03F 7/70133*** (2013.01)

(58) **Field of Classification Search**
CPC G03F 7/70133
See application file for complete search history.

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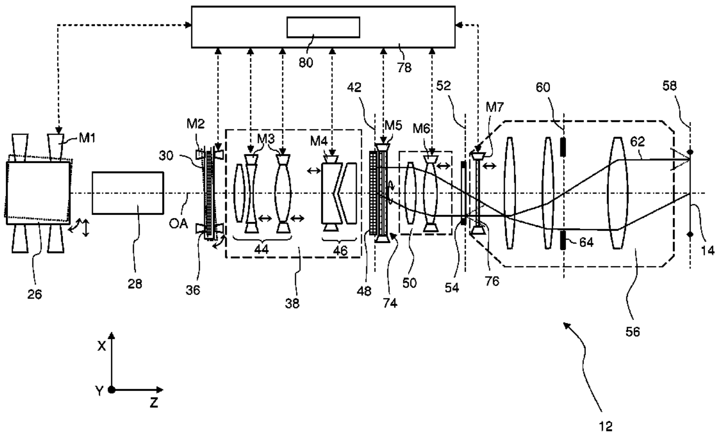
(57) **ABSTRACT**

A method of operating an illumination system of a microlithographic projection exposure apparatus is provided. A set of illumination parameters that describe properties of a light bundle which converges at a point on a mask to be illuminated by the illumination system is first determined. Optical elements whose optical effect on the illumination parameters can be modified as a function of control commands are furthermore determined, as well as sensitivities with which the illumination parameters react to an adjustment of the optical elements, induced by the control commands. The control commands are then determined while taking the previously determined sensitivities into account, such that deviations of the illumination parameters from predetermined target illumination parameters satisfy a predetermined minimization criterion. These control commands are applied to the optical elements, before the mask is illuminated.

30 Claims, 10 Drawing Sheets



Related U.S. Application Data

continuation of application No. PCT/EP2009/000861, filed on Feb. 7, 2009.

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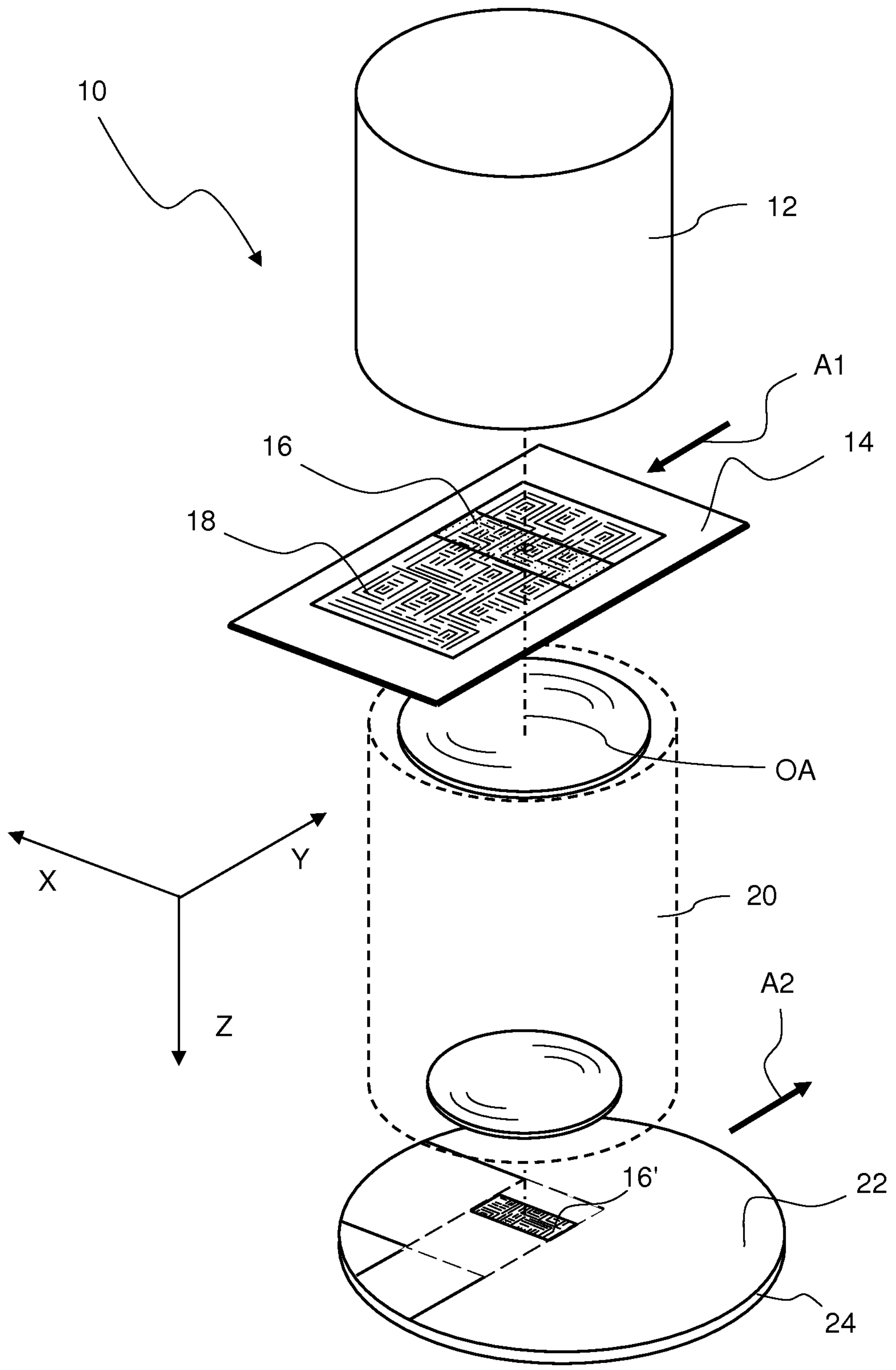

10
12
A1
16
14
18
OA
X
Y
20
Z
A2
16'
22
24

Fig. 1

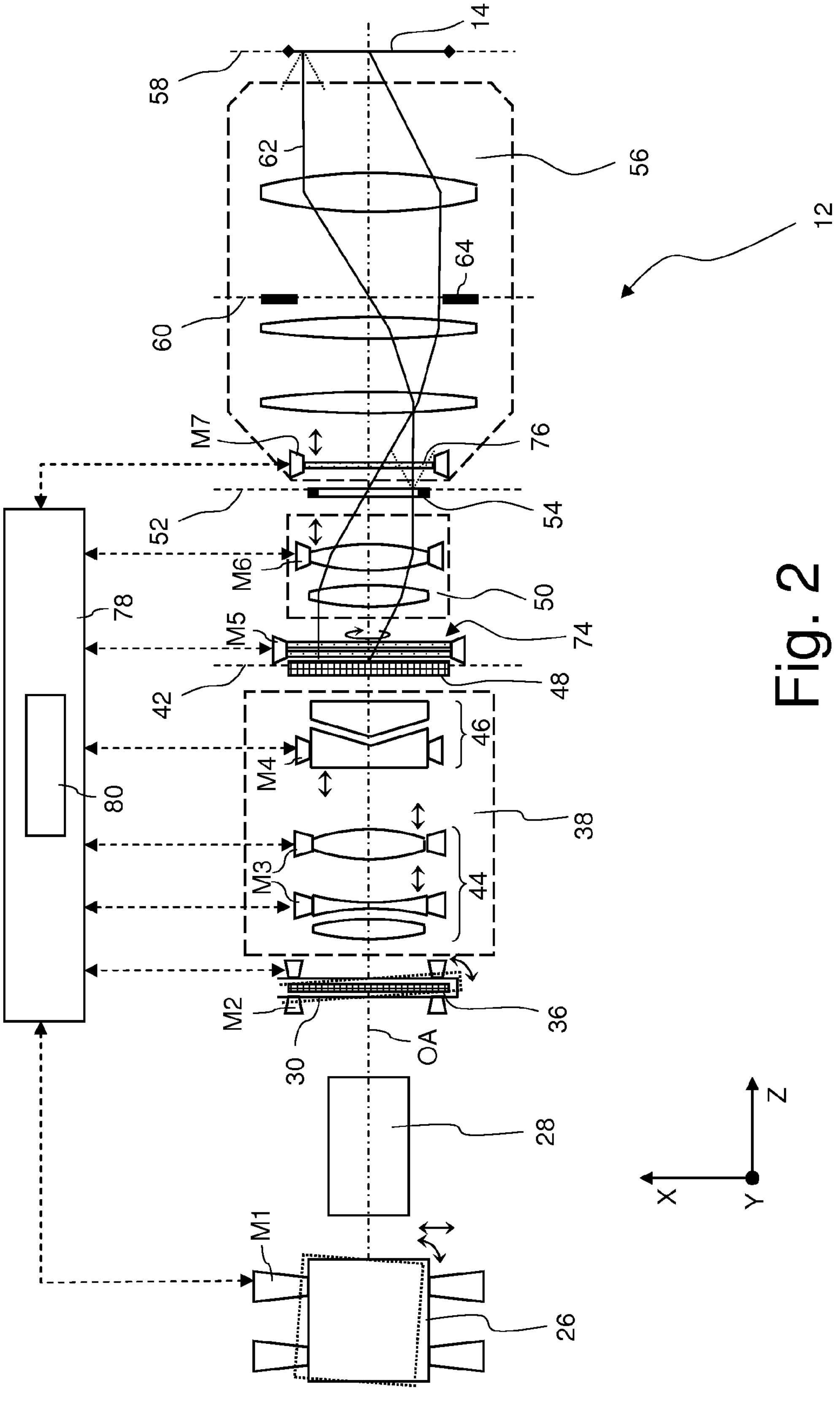

M7
M6
M5
M4
M3
M2
OA
M1
Z
X
Y

Fig. 2

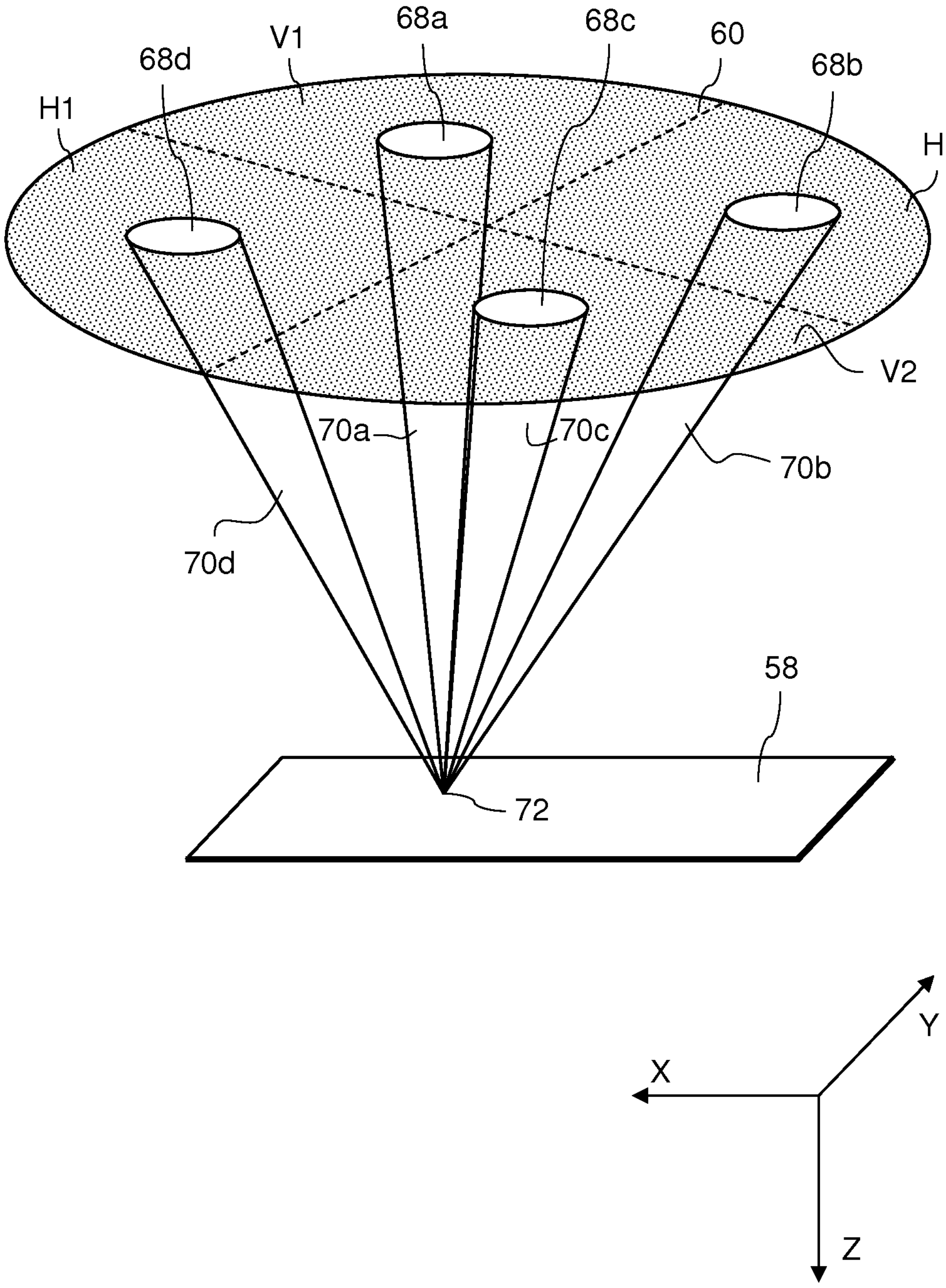

68a
68c
V1
60
68d
68b
H1
H2
V2
70a
70c
70b
70d
58
72
Y
X
Z

Fig. 3

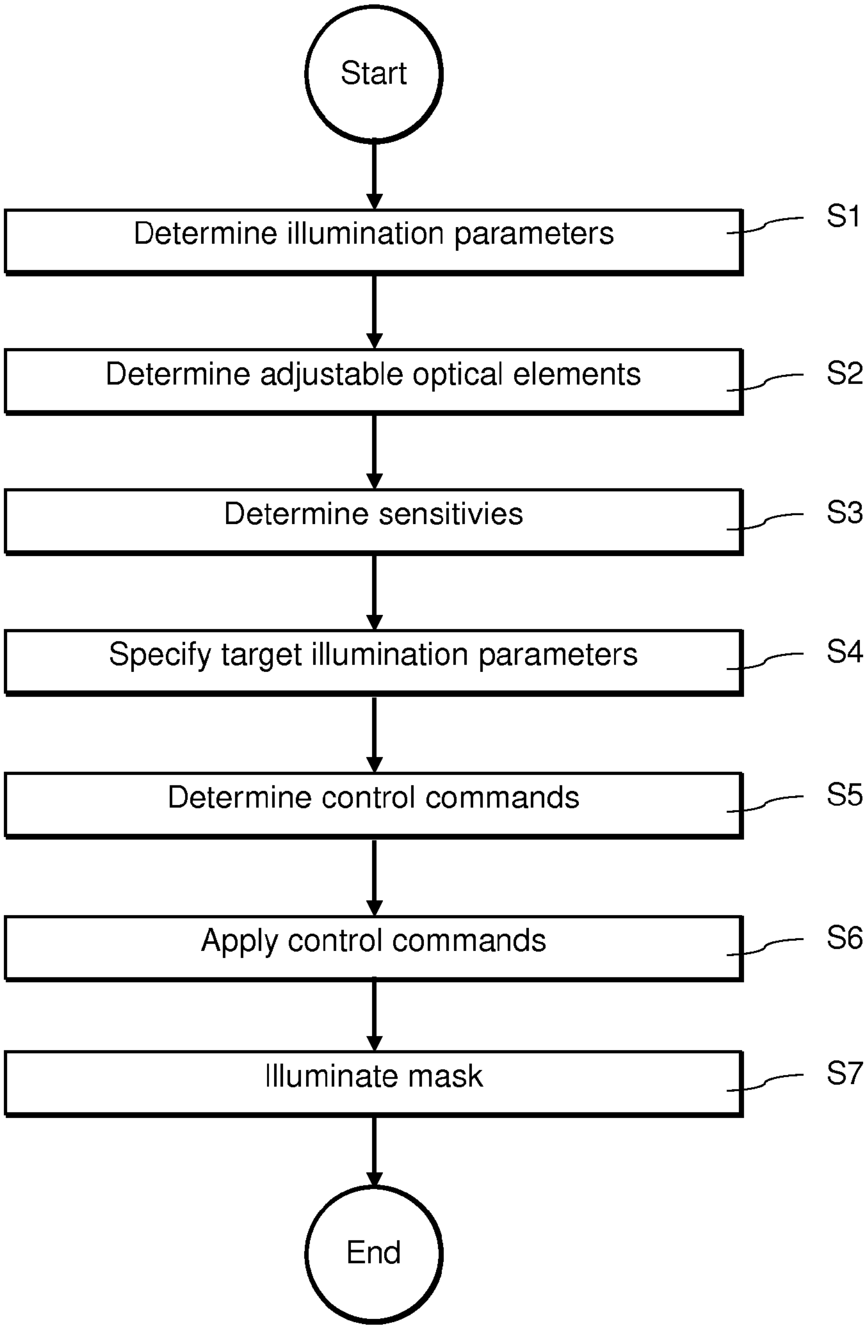

Start
Determine illumination parameters
S1
Determine adjustable optical elements
S2
Determine sensitivies
S3
Specify target illumination parameters
S4
Determine control commands
S5
Apply control commands
S6
Illuminate mask
S7
End

Fig. 4

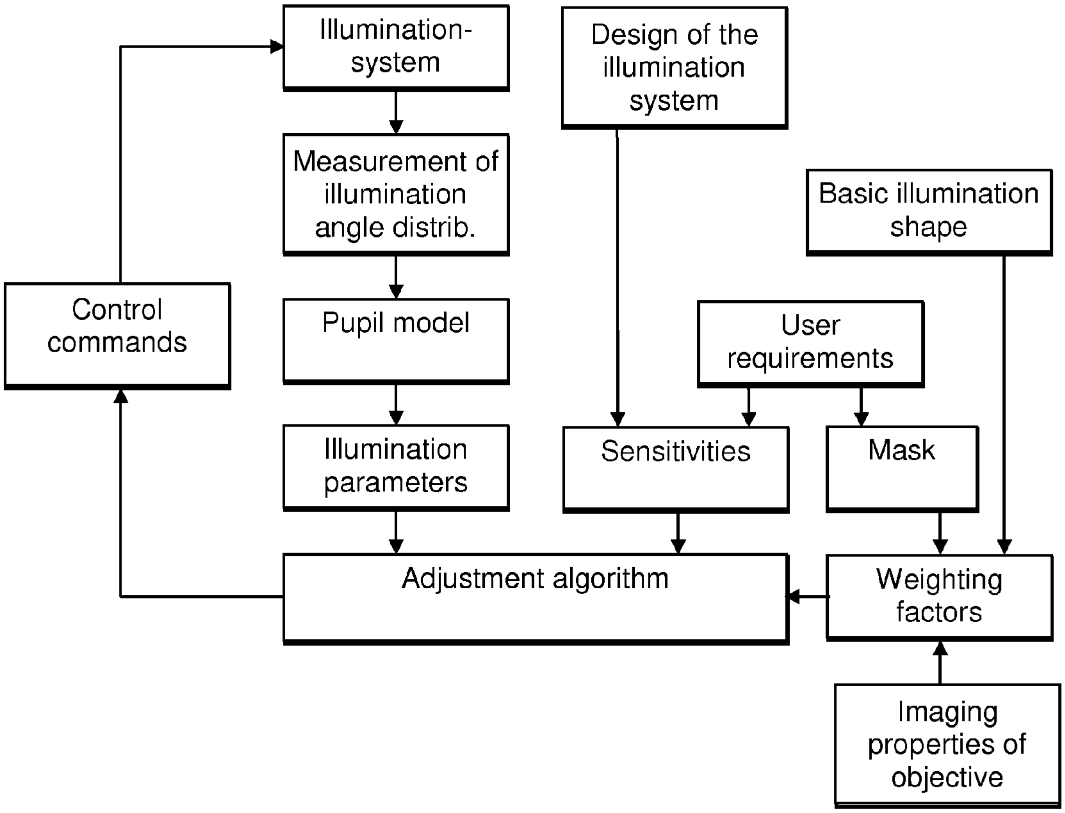

Illumination-system
Design of the illumination system
Measurement of illumination angle distrib.
Basic illumination shape
Control commands
Pupil model
User requirements
Illumination parameters
Sensitivities
Mask
Adjustment algorithm
Weighting factors
Imaging properties of objective

Fig. 5

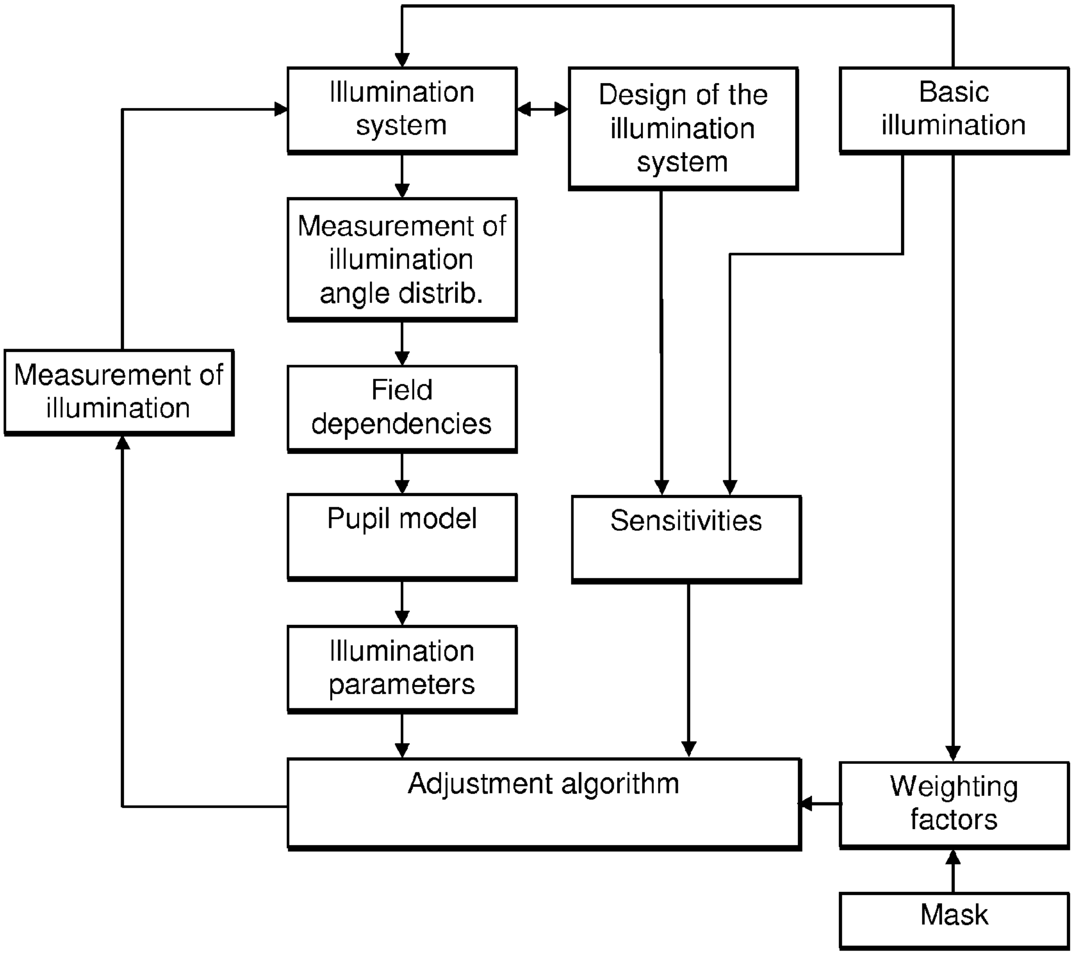

Illumination system
Design of the illumination system
Basic illumination
Measurement of illumination angle distrib.
Measurement of illumination
Field dependencies
Pupil model
Sensitivities
Illumination parameters
Adjustment algorithm
Weighting factors
Mask

Fig. 6

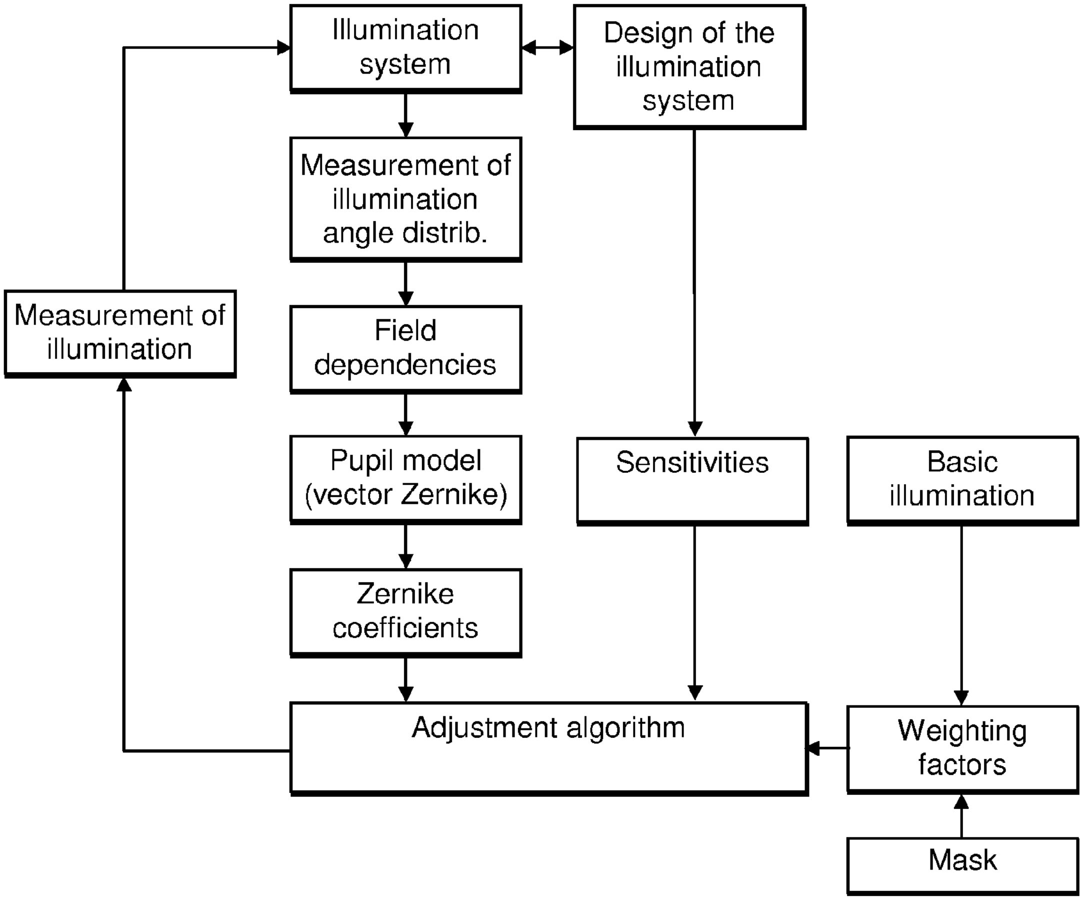
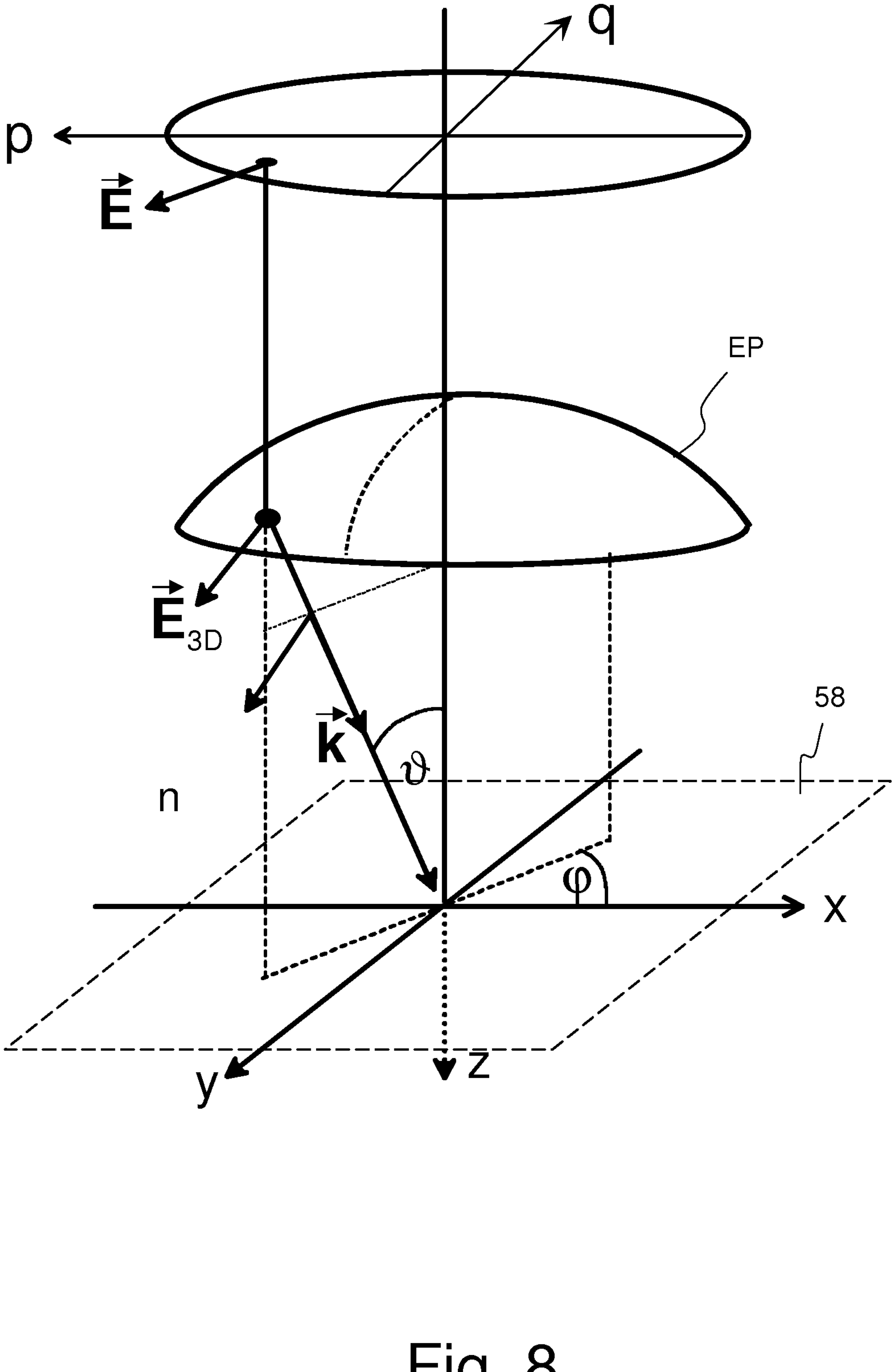

Illumination system
Design of the illumination system
Measurement of illumination angle distrib.
Measurement of illumination
Field dependencies
Pupil model (vector Zernike)
Sensitivities
Basic illumination
Zernike coefficients
Adjustment algorithm
Weighting factors
Mask

Fig. 7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p
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EP
$\vec{E}_{3D}$
58
$\vec{k}$
ϑ
n
φ
x
y
z

Fig. 8

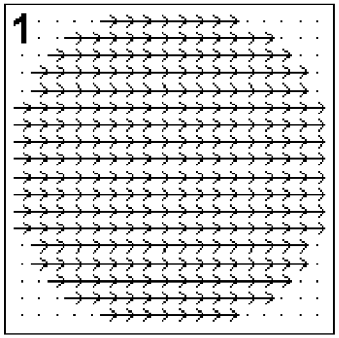

Fig. 9a

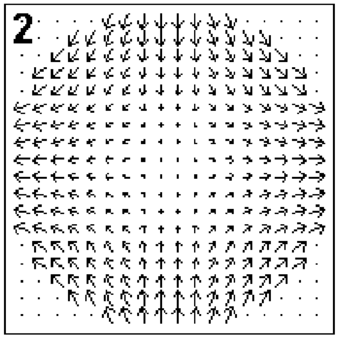

Fig. 9b

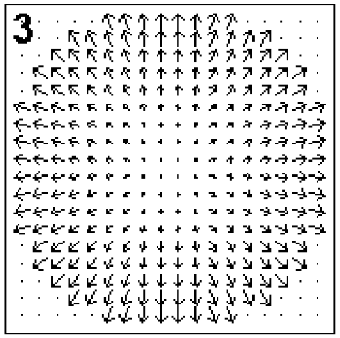

Fig. 9c

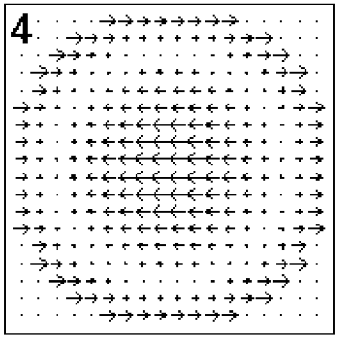

Fig. 9d

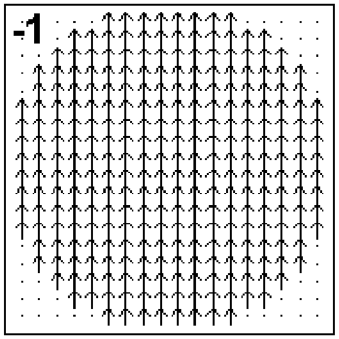

Fig. 10a

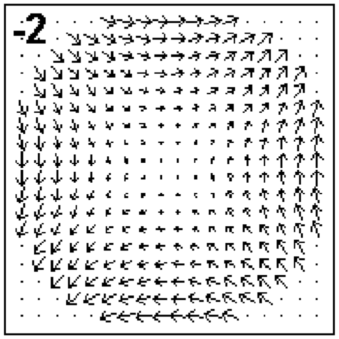

Fig. 10b

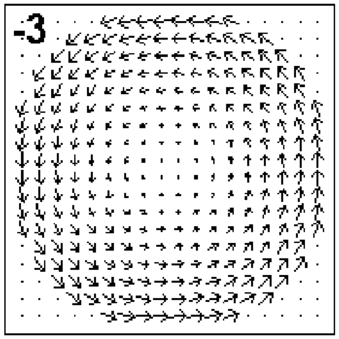

Fig. 10c

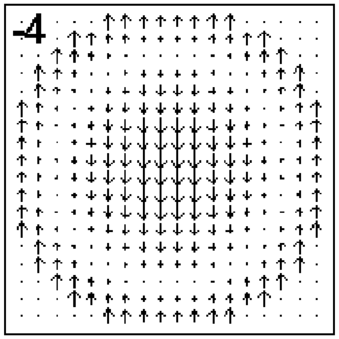

Fig. 10d

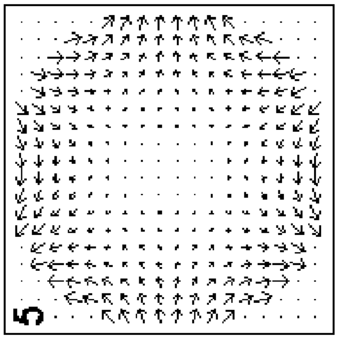

Fig. 9e

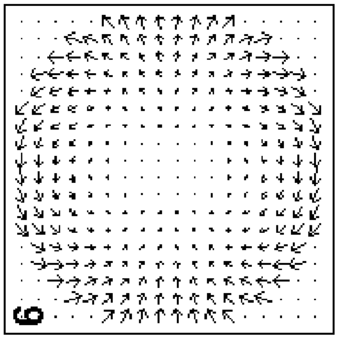

Fig. 9f

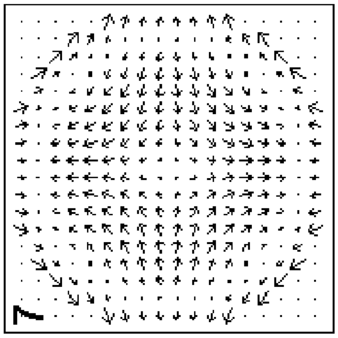

Fig. 9g

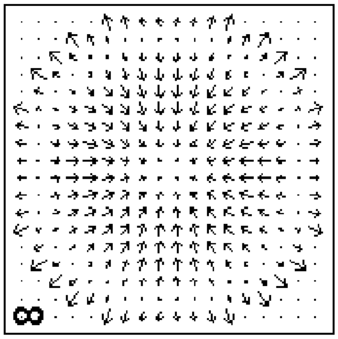

Fig. 9h

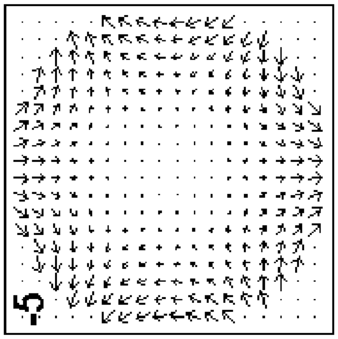

Fig. 10e

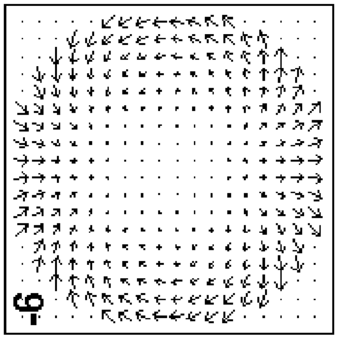

Fig. 10f

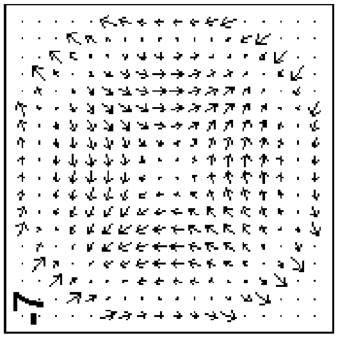

Fig. 10g

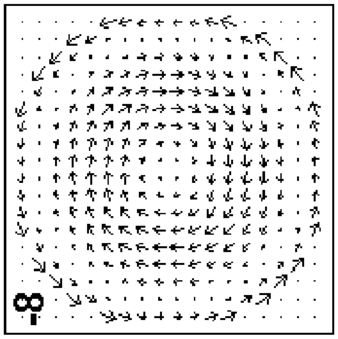

Fig. 10h

METHOD FOR OPERATING AN ILLUMINATION SYSTEM OF A MICROLITHOGRAPHIC PROJECTION EXPOSURE APPARATUS

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation of, and claims benefit under 35 USC 120 to, U.S. application Ser. No. 13/902,100, filed May 24, 2013, which is a continuation of U.S. application Ser. No. 12/853,971, filed Aug. 10, 2010, now U.S. Pat. No. 8,467,033, which is a continuation of, and claims priority under 35 USC 120 to, international application PCT/EP2009/000861, filed Feb. 7, 2009, which claims benefit of German Application No. 10 2008 011 501.0, filed Feb. 25, 2008 and U.S. Ser. No. 61/031,045, filed Feb. 25, 2008. The contents of the prior applications are hereby incorporated by reference in their entirety.

FIELD

The disclosure relates to microlithographic projection exposure apparatus, such as are used for the production of large-scale integrated electrical circuits and other microstructured components. The disclosure relates in particular to methods for operating an illumination system of such a microlithographic projection exposure apparatus.

BACKGROUND

Integrated electrical circuits and other microstructured components are conventionally produced by applying a plurality of structured layers onto a suitable substrate which, for example, may be a silicon wafer. In order to structure the layers, they are first covered with a photoresist which is sensitive to light of a particular wavelength range, for example light in the deep ultraviolet (DUV) spectral range. The wafer coated in this way is subsequently exposed in a projection exposure apparatus. A pattern of diffracting structures, which is arranged on a mask, is thereby imaged onto the photoresist with the aid of a projection objective. Since the imaging scale is generally less than 1, such projection objectives are often also referred to as reducing objectives.

After the photoresist has been developed, the wafer is subjected to an etching process so that the layer becomes structured according to the pattern on the mask. The remaining photoresist is then removed from the other parts of the layer. This process is repeated until all the layers have been applied onto the wafer.

The performance of the projection exposure apparatus being used is determined not only by the imaging properties of the projection objective, but also by an illumination system which illuminates the mask. To this end, the illumination system contains a light source, for example a laser operated in pulsed mode, and a plurality of optical elements which generate light bundles, converging on the mask at field points, from the light generated by the light source. The individual light bundles have particular properties, which in general are adapted to the projection objective.

These properties include inter alia the illumination angle distribution of the light bundles which respectively converge on a point in the mask plane. The term illumination angle distribution describes the way in which the overall intensity of a light bundle is distributed between the different directions in which the individual rays of the light bundle strike the relevant point in the mask plane. If the illumination angle distribution is specially adapted to the pattern contained in the mask, then the latter can be imaged with high imaging quality onto the wafer covered with photoresist.

The illumination angle distribution is often described not directly in the mask plane, in which the mask to be projected is placed, but instead as an intensity distribution in a generalised pupil or a real pupil surface, which has a Fourier relation with the mask plane. The generalised pupil corresponds to an exit pupil lying at infinity, whereas a real pupil surface is distinguished in that the principal rays of the ray bundles intersect the optical axis there. Description of the illumination angle distribution (angle space) with the aid of an intensity distribution (position space) utilises the fact that each angle with respect to the optical axis, at which a light ray passes through a field plane, can be assigned a radial distance measured from the optical axis in a Fourier-transformed pupil surface. Similar considerations also apply to a generalised pupil. For the sake of simplicity, in what follows the description of the illumination angle distribution will refer to the intensity distribution in a real pupil surface, unless expressly indicated otherwise.

The illumination angle distribution, or the intensity distribution equivalent thereto in a pupil surface or idealised exit pupil, will sometimes also be referred to as an "illumination setting". Depending on the basic shape of the intensity distribution, distinction is made between so-called conventional and unconventional illumination settings.

In the case of conventional illumination settings, the intensity distribution in a pupil surface has the shape of a circular disc concentric with the optical axis. Each point in the mask plane is therefore struck by light rays at angles of incidence of between 0° and a maximum angle dictated by the radius of the circular disc. In the case of unconventional illumination settings, which include in particular ring-field illuminations and multi-pole illuminations, the region illuminated in the pupil surface has the shape of a ring concentric with the optical axis, or a plurality of individual regions (poles) which are arranged at a distance from the optical axis. With these settings, therefore, the mask to be projected is only illuminated obliquely. In the case of dipole illumination, for example, two poles are arranged on a radius with an equal radial distance from the optical axis. The intensity distribution for quadrupole illumination is obtained as a superposition of two dipole illuminations mutually rotated by 90°.

The operators of projection exposure apparatus generally establish a target illumination angle distribution, which is regarded as particularly suitable for imaging a particular mask optimally with the aid of a projection objective onto a photoresist or another photosensitive layer. The task is then to adjust the illumination system so that the target illumination distribution is achieved with the greatest possible accuracy in the mask plane. To this end, illumination systems generally include a plurality of adjustable optical elements whose optical effect on the illumination angle distribution can be modified as a function of control commands. These optical elements may for example be replaceable diffractive optical elements, zoom objectives and/or pairs of axicon elements. Additional measures are furthermore often provided, by which fine tuning or correction of the illumination angle distribution can be achieved. In this context, for example, U.S. Pat. No. 6,535,274 B2 proposes adjustable transmission filters which are arranged in or in the immediate vicinity of the pupil surface.

The greater the number of optical elements, whose effect on the illumination angle distribution can be modified as a function of control commands, the more difficult it is to determine the control commands so that the illumination angle distribution actually set up corresponds as much as possible to the target illumination angle distribution. This problem is encountered above all when new types of illumination angle distributions are intended to be set up, for which there is not yet any experience as to the control commands with which the new type of illumination angle distribution can be achieved.

To date, attempts have been made to describe the illumination angle distribution for the various illumination settings with the aid of relatively simple models. Various quantities have been defined, which can be deliberately influenced with the aid of particular optical elements, for example filter elements arranged near the pupil. In the case of conventional, annular or quadrupole illumination settings, for example, a quantity referred to as the pupil ellipticity is often employed. Simply speaking, the pupil ellipticity corresponds to the ratio of the amounts of light which strike a field point on the mask from orthogonal directions during exposure. The greater the pupil ellipticity deviates from 1, the more asymmetric is the illumination angle distribution.

Another quantity, which has to date been employed for describing illumination angle distributions, is the telecentricity. Illumination is referred to as energetically telecentric when the energetic central rays of the light bundles, which are often also referred to as centroid rays, pass perpendicularly through the mask plane. Similar considerations apply to the geometrical telecentricity, for which it is not the energetic but the geometrical central rays (i.e. principal rays) of the light bundles which are considered.

In the case of energetically non-telecentric illumination, the entire light bundles strike the mask to some extent obliquely. For the illumination angle distribution, this means that the amounts of light coming from opposite directions are of different size. In general, telecentric illumination is desired since the projection objectives are usually likewise telecentric on the object side.

Such quantities, however, sometimes cannot be used expediently for all illumination settings. Above all, these quantities generally do not allow the intensity distribution in the pupil surface (and therefore the illumination angle distribution in the mask plane) to be described so accurately that the intensity distribution could be reconstructed based on these quantities.

An article by T. Heil et al. entitled "*Predictive modeling of advanced illumination pupils used as imaging enhancements for low-k*1 *applications*", Optical Microlithography XVII, B. W., Smith, ed., Proc SPIE 5377, pages 344-356, SPIE, March 2004 discloses a parametric pupil model with which annular illumination settings can be described very precisely. With the aid of a relatively limited number of pupil parameters, it is possible to describe ring-shaped intensity distributions in a pupil surface so accurately that the intensity distribution can be reconstructed merely based on the illumination parameters. This article does not, however, address the question of how control commands are to be determined for adjustable optical elements, so that a desired target illumination angle distribution is achieved in the mask plane.

SUMMARY

The disclosure provides a method for operating an illumination system of a microlithographic projection exposure apparatus which makes it possible to determine the control commands for optical elements to try to set the properties of a light bundle, which converges at a point on a mask to be illuminated by the illumination system, to be the properties specified by a target illumination angle distribution.

The disclosure provides a method that includes:

a) determining a set of illumination parameters that describe properties of a light bundle which converges at a point on a mask to be illuminated by the illumination system, wherein the properties of the light bundle include an intensity distribution which the light bundle has in an exit pupil associated to the point, the intensity distribution being described as a perturbation of an ideal intensity distribution;

b) determining optical elements whose optical effect on the illumination parameters can be modified as a function of control commands;

c) for each optical element, determining sensitivities with which the illumination parameters react to an adjustment, which is induced by the control commands, of the respective optical element;

d) specifying a set of target illumination parameters;

e) determining the control commands, while taking into account the sensitivities determined in step c), such that deviations of the illumination parameters from the target illumination parameters satisfy a predetermined minimisation criterion;

f) applying the control commands determined in step e) to the optical elements;

g) illuminating the mask.

The disclosure also provides a method for evaluating properties of a light bundle which converges at a point on a mask to be illuminated by an illumination system in a microlithographic projection exposure apparatus.

The disclosure provides a method that includes:

a) measuring an intensity distribution in an exit pupil of the illumination system, which is assigned to the point;

b) at least approximately describing the intensity distribution measured in step a) as a perturbation of an ideal intensity distribution, the perturbation being described as a combination of an intensity modulation and a distortion, and wherein
  i) the intensity modulation is described by a linear superposition of functions of a first complete, optionally orthogonal function system and
  ii) the distortion is described by linear superposition of vector modes of a complete, optionally orthogonal second function system;

c) evaluating the properties of the light bundle based on scalar superposition coefficients of the linear superpositions.

Such evaluation may also be helpful in the production of an illumination system. The disclosure provides a production method that includes:

compiling a design for the illumination system;

evaluating the properties of a light bundle according to the evaluation method indicated above;

determining a quality function to which at least one of the superposition coefficients determined in step b) contributes;

compiling a modified design such that the quality function is improved.

By additional adjustment steps after production and before delivery, an illumination system may be improved further in respect of the properties of a light bundle which converges at a point on a mask to be illuminated by the illumination system. To this end, the following steps may be provided:

evaluating properties of a light bundle according to the evaluation method indicated above;

modifying the properties such that the evaluation is improved.

The disclosure further provides a microlithographic projection exposure apparatus which makes it possible to determine control commands for optical elements of an illumination system to try to set the properties of a light bundle, which converges at a point on a mask to be illuminated by the illumination system, to be the properties specified by a target illumination angle distribution.

The disclosure provides a projection exposure apparatus having:

- an illumination system which contains a plurality of optical elements whose optical effect on the illumination parameters can be modified as a function of control commands,
- a measuring instrument for measuring an intensity distribution in an exit pupil which is assigned to a point that lies in an illumination plane, in which a mask to be illuminated can be arranged, and at which a light bundle converges,
- a computer by which is configured
  - (i) to determine, for each optical element, sensitivities with which illumination parameters, which describe properties of the light bundle, react to an adjustment, which is induced by the control commands, which is induced by the control commands, of the respective optical element, wherein the properties of the light bundle include an intensity distribution which the light bundle has in an exit pupil associated to the point, the intensity distribution being described as a perturbation of an ideal intensity distribution, and wherein the computer is further configured
  - (ii) to control commands can be determined while taking the previously determined sensitivities into account, such that deviations of the illumination parameters from the target illumination parameters satisfy a predetermined minimisation criterion;
- a data transfer path via which the control commands determined by the computer can be applied to the optical elements.

The disclosure furthermore relates to a method for configuring a mask which is intended to be illuminated by an illumination system in a microlithographic projection exposure apparatus and imaged onto a photosensitive layer by a projection objective. According to the disclosure, such a method includes the following steps:

- a) evaluating properties of a light bundle which converges at a point on the mask to be illuminated by the illumination system in the microlithographic projection exposure apparatus, according to the evaluation method indicated above;
- b) determining structures contained on the mask while taking the superposition coefficients into account, so as to reduce undesired effects on the imaging of the mask which are caused by at least one non-zero superposition coefficient.

BRIEF DESCRIPTION OF THE DRAWINGS

Other features and advantages of the disclosure may be found in the following description of an exemplary embodiment with reference to the drawing, in which:

FIG. **1** shows a highly simplified perspective representation of a microlithographic projection exposure apparatus;

FIG. **2** shows a meridian section through an illumination system of the projection exposure apparatus shown in FIG. **1**, according to a first exemplary embodiment;

FIG. **3** shows a perspective representation of a plurality of light bundles emerging from a pupil surface;

FIG. **4** shows a flowchart to explain a method according to the disclosure;

FIG. **5** shows a diagram which presents essential quantities of the method represented as a flowchart in FIG. **4**, according to a first exemplary embodiment;

FIG. **6** shows a diagram corresponding to FIG. **5** according to a second exemplary embodiment;

FIG. **7** shows a diagram corresponding to FIG. **5** according to a third exemplary embodiment;

FIG. **8** shows an illustration to clarify the geometrical relationships between the exit pupil and the image plane;

FIGS. **9***a* to **9***h* show graphs in which vector Zernike polynomials are plotted for order numbers 1 to 8;

FIGS. **10***a* to **10***h* show graphs in which vector Zernike polynomials are plotted for order numbers −1 to −8.

DETAILED DESCRIPTION

1. Structure of a Projection Exposure Apparatus

FIG. **1** shows a highly schematised perspective representation of a projection exposure apparatus **10**, which is suitable for the lithographic production of microstructured components. The projection exposure apparatus **10** contains an illumination system **12** that illuminates a narrow illumination field **16**, which is rectangular in the exemplary embodiment represented, on a mask **14**. Other illumination field shapes, for example ring segments, may of course likewise be envisaged.

Structures **18** lying inside the illumination field **16** on the mask **14** are imaged with the aid of a projection objective **20** onto a photosensitive layer **22**. The photosensitive layer **22**, which may for example be a photoresist, is applied on a wafer **24** or another suitable substrate and lies in the image plane of the projection objective **20**. Since the projection objective **20** generally has an imaging scale $|\beta|<1$, the structures **18** lying inside the illumination field **16** are imaged in a reduced fashion as region **16'**.

In the projection exposure apparatus **10** represented, the mask **14** and the wafer **24** are displaced along a direction denoted by Y during the projection. The ratio of the displacement speeds is equal to the imaging scale β of the projection objective **20**. If the projection objective **20** generates inversion of the image (i.e. $\beta<0$), then the displacement movements of the mask **14** and the wafer **22** will be in opposite directions as is indicated by arrows A**1** and A**2** in FIG. **1**. In this way, the illumination field **16** is guided in a scanning movement over the mask **14** so that even sizeable structured regions can be projected coherently onto the photosensitive layer **22**.

2. Structure of an Illumination System

FIG. **2** shows details of the illumination system **12** in a simplified meridian section which is not true to scale. The illumination system **12** contains a light source **26**, which generates projection light. In the exemplary embodiment described here, the light source **26** is an excimer laser with which light in the (deep) ultraviolet spectral range can be generated. The use of short-wave projection light is advantageous because a high resolution can thereby be achieved for the optical imaging. Excimer lasers with the laser media KrF, ArF or F_2, by which light with the wavelengths 248 nm, 193 nm and 157 nm can respectively be generated, are conventional.

The light generated by the excimer laser used as a light source **26** is highly collimated and diverges only weakly. It is therefore initially expanded in a bundle expander **28**. The bundle expander **28** may for example be an adjustable mirror arrangement, which increases the dimensions of the approximately rectangular light bundle cross section.

The expanded light bundle subsequently passes through a diffractive optical element **36**, held in an exchange holder **30**, and a zoom-axicon module **38**, which together illuminate a first pupil surface **42** of the illumination system. The zoom-axicon module **38** includes a zoom objective denoted by **44** and an axicon group **46**, which contains two axicon elements with conical and mutually complementary faces. With the aid of the axicon group **46**, the radial light distribution can be modified so as to achieve ring-shaped illumination of the first pupil surface **42**. By adjusting the zoom objective **44**, it is possible to modify the diameter of the regions illuminated in the first pupil surface **42**. The zoom-axicon module **38** therefore makes it possible to set up various conventional and annular illumination settings.

In order to set up multi-pole illumination settings, in the illumination system represented, a diffractive optical element **36** is inserted into the exchange holder **30**. The structures on the diffractive optical element **36** are arranged so that the desired multi-pole intensity distribution is generated in the far-field.

An optical integrator **48**, which may for example be an arrangement of microlens arrays, is arranged in or in the immediate vicinity of the first pupil surface **42**. The optical integrator generates secondary light sources in its focal plane on the image side, each of which emits a divergent light bundle with an angle spectrum dictated above all by the geometry of the microlenses. By a condenser **50**, the light bundles generated by the secondary light sources are superimposed in an intermediate field plane **52** so that it is illuminated very homogeneously. The condenser **50** establishes a Fourier relation between the first pupil surface **42** and the intermediate field plane **52**. All light rays coming from the first pupil surface **42** at the same angle therefore arrive at the same point in the intermediate field plane **52**, whereas all light rays coming from a particular point in the first pupil surface **42** pass through the intermediate field plane **52** at the same angle.

In the exemplary embodiment represented, a field diaphragm **54**, which may for example include a plurality of adjustable blades and/or a multiplicity of narrow finger-like diaphragm elements that can be inserted independently of one another into the light path, is arranged in the intermediate field plane **52**. With the aid of a field diaphragm objective **56**, the intermediate field plane **52** is optically conjugated with a mask plane **58** in which the mask **14** is arranged. The mask plane **58** is both the image plane of the field diaphragm objective **56** and the object plane of the subsequent projection objective **20**.

The field diaphragm objective **56** contains a second pupil surface **60** of the illumination system **12**, in which an aperture diaphragm **64** may be arranged in order to (additionally) restrict the numerical aperture of the illumination system **12** on its image side.

3. Illumination Angle Distribution

The illumination system **12** allows the properties of light bundles, which respectively converge at points on the mask **14** to be illuminated by the illumination system **12**, to be established with high accuracy. These properties are, on the one hand, the overall intensity with which the light bundles strike the mask **14**. Uncontrolled variations in the overall intensity of the individual light bundles can lead to undesired variations in the width of the structures which are generated on the wafer **24**.

It is not however the overall intensity which will be the centre of attention in what follows, but instead a property of the light bundles which is referred to as the illumination angle distribution. The term "illumination angle distribution" describes the way in which the overall intensity of a light bundle is distributed between the different directions along which the individual rays of the light bundle strike a point on the mask. What this means will be explained below with reference to FIG. **3**.

FIG. **3** shows, in a perspective schematic representation, the pupil surface **60** of the field diaphragm objective **56** as well as a detail of the mask plane **58**. For this representation, it is assumed that quadrupole illumination is being generated by the illumination system **12**. As already mentioned above, to this end the diffractive optical element **36** may be configured so that four poles are illuminated in the first pupil surface **42**. Since the basic shape of the illumination angle distribution is not changed by the optical elements arranged between the first pupil surface **42** and the second pupil surface **60**, four poles are also illuminated in the pupil surface **60** of the field diaphragm objective **56**, which are denoted by **68***a*, **68***b*, **68***c* and **68***d* in FIG. **3**. The light sub-bundles which illuminate the poles **68***a* to **68***d* are denoted by **70***a*, **70***b*, **70***c* and **70***d*, respectively and they converge at a field point **72** in the mask plane **58**. All the light sub-bundles **70***a* to **70***d* therefore contribute to the intensity at the field point **72**.

In quadrupole illumination, it is generally desirable that all the light sub-bundles **70***a* to **70***d* should contribute in the same way to the intensity at the field point **72**. Only this will ensure that strip-like structures in the mask **14**, which have equal widths but different orientations (vertical or horizontal), are also imaged with equal widths onto the photosensitive layer **22**. If the contributions of the light sub-bundles **70***a* and **70***c* are greater or less than the contributions of the light bundles **70***b* and **70***d*, then for example the situation may arise that horizontally oriented structures are projected onto the photosensitive layer **22** with a greater width than vertically oriented structures, even though in both cases the structures have equal widths in the mask **14**.

In order to be able to describe the intensity distribution on the four poles **68***a* to **68***d*, especially in the case of quadrupole illumination, to date the pupil surface **60** (or more accurately the exit pupils assigned to the individual mask points, more details below) is divided into quadrants V**1**, V**2**, and H**1**, H**2** in which a pole **68***a* to **68***d* is respectively arranged. The mutually opposite quadrants V**1**, V**2**, and H**1**, H**2** then contain a pair of poles, the light of which leads only to the imaging of structures with a particular structure direction. By specifying the intensity of the light passing through the quadrants V**1**, V**2** and H**1**, H**2**, it is therefore possible to draw conclusions as to whether the light fractions which lead to the imaging of structures extending mutually orthogonally are equal or not. This ratio is referred to as the pupil ellipticity E, and it can be used as a parameter for describing a property of the illumination angle distribution. In the case of quadrupole illumination, however, it will generally be desirable to employ further illumination parameters in order to describe the illumination angle distribution.

For other basic shapes of intensity distributions in pupil surfaces of the illumination system **12**, for instance in the case of conventional, annular or dipole illumination settings, it is likewise desirable to find illumination parameters which allow simple but nevertheless maximally complete description of the intensity distribution. A set of illumination parameters suitable for annular illumination settings is specified in the article by T. Heil et al. which was mentioned in the introduction. There, the intensity distribution is described with the aid of a parameter-based pupil model in which some of the parameters describe an ideal ring-shaped intensity distribution and the other parameters relate to perturbations, i.e. deviations from this ideal intensity distribution. Below, in section 6.2, a new pupil model will also be explained which allows very accurate description of illumination angle distributions irrespective of any particular basic shape of an intensity distribution in a pupil surface.

4. Influencing the Illumination Angle Distribution

In order to be able to adjust the illumination angle distribution, the illumination system **12** includes a plurality of adjustable optical elements whose optical effect on the illumination angle distribution, and therefore on the illumination parameters used to describe it, can be modified as a function of control commands. In general the modified effect will be due to a position change of the relevant optical element, for example displacements, rotations or tilts, induced with the aid of manipulators. Material properties may also be used instead of position changes, for example the refractive index by applying an electrical voltage (electro-optical effect). Those optical elements of the illumination system **12** with which the illumination angle distribution can be adjusted, will be explained briefly below in sequence in the light path.

With the aid of first manipulators M**1**, as indicated by small arrows, the light source **26** can be displaced in translation perpendicularly to the optical axis OA and/or tilted about a tilt axis extending perpendicularly to the optical axis OA. Tilting changes the direction of the light rays which strike the diffractive optical element **36**. Owing to this different illumination, the angle distribution generated by the diffractive optical element **36** also changes. Overall, displacing the light source **26** in translation perpendicularly to the optical axis OA shifts the intensity distribution in the pupil surfaces **42** and **60**.

The exchange holder **30** for the diffractive optical element **36** can furthermore be tilted about a tilt axis extending perpendicularly to the optical axis OA with the aid of second manipulators M**2**, as is likewise indicated by a small arrow. The effect on the illumination angle distribution due to this differs from that which is generated by tilting the light source **26**.

The zoom objective **44**, with which the intensity distribution in the first pupil surface **42** can be varied by modifying the focal length of the zoom objective **44**, is particularly important for adjustment of the illumination angle distribution. To this end, the zoom objective **44** includes two third manipulators M**3** working together, with which the axial position of at least two lenses of the zoom objective **44** can be modified.

With the aid of the axicon group **46**, different annular intensity distributions can be generated in the first pupil surface **42** as already explained above in 2. The distance between the two axicon elements of the axicon group **46** can be modified by a fourth manipulator M**4**, and has an effect on the ring diameter as well as the ring width of the annular intensity distribution.

In or in the immediate vicinity of the first pupil surface **42**, the pupil filter **74** is arranged which contains two filter elements that can be rotated relative to one another (see arrow). The relative rotation setting of the two filter elements can be modified with the aid of a fifth manipulator M**5**. Details regarding the pupil filter **74** may be found in U.S. Pat. No. 6,535,274 B2, which has already been mentioned above. The filter elements of the pupil filter **74** are designed as transmission filters which, in some exemplary embodiments, include grey filter regions in the form of circle segments. With such filters the illumination angle distribution can be corrected field-independently, i.e. with the same effect over the entire mask **14**, within certain limits.

In the illumination system **12**, in order to adjust the illumination angle distribution, a sixth manipulator M**6** is furthermore provided with which one or more lenses inside the condenser **50** can be displaced in an axial direction. Deviations from the sine condition can deliberately be induced by such a displacement, so that the relation between positions in the first pupil surface **42** on the one hand, and angles in the subsequent intermediate field plane **52** on the other hand, can be modified.

Behind the intermediate field plane **52**, an intermediate filter **76** is arranged which is likewise designed as a transmission filter, although it is arranged neither in a pupil surface nor in a field plane in its axial position. Owing to this arrangement, the intermediate filter **76** influences the illumination angle distribution field-dependently i.e. the effect on the illumination angle distribution differs for different points on the mask **14**. Undesired effects on the intensity distribution on the mask **14** may be compensated for by additional measures. Details regarding the intermediate filter **76** may be found from WO 2008/092653 A assigned to the Applicant. This also describes multi-part intermediate filters **76**, in which individual parts of the intermediate filter **76** can be displaced with the aid of a seventh manipulator M7 so that the field-dependent effect on the illumination angle distribution can be modified within certain limits, without this affecting the intensity distribution. The seventh manipulator M7 may also be designed so that it can extract the intermediate filter **76** fully from the bundle path.

The manipulators M**1** to M**7** are connected via signal lines (represented by dashes) to a control unit **78** by which the individual manipulators M**1** to M**7** can be driven in a controlled fashion. To this end, the control unit **78** includes a computer **80** which, according to a method explained below, ascertains the control commands which are applied to the manipulators M**1** to M**7** so that the illumination system **12** generates a desired target illumination angle distribution in the mask plane **58**.

5. Method for Determining the Control Commands

A first exemplary embodiment of a method, with which the desired illumination angle distribution in the mask plane **58** can be generated by suitable driving of the manipulators M**1** to M**7**, will be described below with the aid of the flowchart shown in FIG. **4** and the diagram of FIG. **5**. The method is based on an adjustment algorithm in which properties of light bundles, namely in particular the illumination angle distribution, can be described with the aid of illumination parameters. With the aid of a minimisation criterion, control commands for the manipulators M**1** to M**7** are determined such that the actual illumination parameters approximate predetermined target illumination parameters. The essential method steps will first be described at length; other exemplary embodiments of such a method will be explained further below in section 6.

(a) Determining the Illumination Parameters

In a first step S**1** a set of illumination parameters is determined, which describe properties of the light bundles that converge at points on the mask **14** to be illuminated by the illumination system **12**. As already mentioned in 4, to this end it is possible to use different pupil models with which the illumination angle distribution in a pupil surface can be described parametrically.

The illumination parameters not only are suitable for describing the properties of the illumination angle distribution, but should also be acquirable via measurements (at least indirectly). A measurement of the illumination angle distribution is conventionally carried out by introducing an angle-resolving sensor, which measures the illumination angle distribution at a selected point in the mask plane **58**, into the mask planes **58** or in the image plane of the projection objective. To this end, the sensor may contain a condenser which converts the angle distribution at the selected point into a position distribution in a plane, in which a position-resolving 2D sensor is arranged.

Ideally the illumination parameters should be determined so that they can be input quantities of a simulation program, with which the dimensions of images of the structures **18** contained on the mask **14** can be calculated. The pupil ellipticity E is such a quantity, since with knowledge of this quantity and further boundary conditions (imaging properties of the projection objective, illumination threshold of the photosensitive layer **22** etc.) it is possible to calculate how greatly the dimensions of structures, which per se are of the same type but extend mutually orthogonally, will differ from one another in the event of a pupil ellipticity $E \neq 1$.

In what follows, it will be assumed that m illumination parameters $p_1, \ldots, p_m$ are determined, which represent components of a vector $\vec{p}$ that combines the set of illumination parameters.

(b) Determining the Adjustable Optical Elements

In a second step S**2**, those adjustable optical elements are determined whose optical effect on the illumination parameters can be modified as a function of control commands. In the illumination system **12**, this selection is established by the manipulators M**1** to M**7**.

The control commands which are assigned to the individual manipulators, and which respectively lead to a particular adjustment of the relevant manipulator, will be denoted as $x_1, \ldots, x_n$, where n is less than or equal to the total number of manipulators. The set of control commands $x_1, \ldots, x_n$ will be combined to form a vector $\vec{x}$.

(c) Determining the Sensitivities

For determining the control commands, it will be assumed that the control commands $x_1, \ldots, x_n$ act approximately linearly according to equation Eq. (1)

$$\begin{pmatrix} x_1 \\ \vdots \\ x_n \end{pmatrix} \cdot \begin{pmatrix} s_{11} & \ldots & s_{1m} \\ \vdots & \ddots & \vdots \\ s_{n1} & \ldots & s_{nm} \end{pmatrix} = \begin{pmatrix} p_1 \\ \vdots \\ p_m \end{pmatrix} \tag{1}$$

or in matrix vector notation

$$\vec{x} \cdot \overleftrightarrow{S} = \vec{p}$$

on the illumination parameters $p_1, \ldots, p_m$. The matrix $\overleftrightarrow{S}$ contains sensitivities s_{ij}, which describe how the control commands affect the various illumination parameters $p_1, \ldots, p_m$. The sensitivity matrix $\overleftrightarrow{S}$ is now determined in a step S3 by simulation or by measurement.

Determination by simulation may, for example, be carried out by only the control commands assigned to a particular manipulator being varied and ascertaining by simulation how the changes affect the various illumination parameters $p_1, \ldots, p_m$. For determination by measurement a similar procedure may be adopted, i.e. a manipulator is driven with different control commands and the illumination angle distribution obtained for one field point or a multiplicity of field points is respectively acquired by measurement techniques. The illumination parameters $p_1, \ldots, p_m$ are then derived from the measured illumination angle distribution according to the pupil model being employed.

(d) Specifying the Target Illumination Parameters

In a step S**4** target illumination parameters are specified, which describe the target illumination angle distribution to be set up in the mask plane **58**. The set of target illumination parameters will be denoted below as the vector $\vec{p}_0$.

(e) Determining the Control Commands

In a further step S**5** a set $\vec{x}$ of control commands is determined, while taking into account the sensitivities determined in step S**3**, such that deviations of the set $\vec{p}$ from the set $\vec{p}_0$ of target illumination parameters satisfy a predetermined minimisation criterion. In the simplest case, the expression

$$\|\vec{x} \cdot \overleftrightarrow{S} - \vec{p}\| \tag{2}$$

is minimised, where $\|\cdot\|$ denotes the conventional Euclidean 2-norm. Linear algebra provides a range of solution methods for solving the minimisation problem. One conventional method is to determine the pseudo-inverses via singular value decomposition. If the control commands $\vec{x}$ are selected so that, taking the sensitivity matrix $\overleftrightarrow{S}$ into account, they lead to an illumination angle distribution in the mask plane **58** which is described by the target parameters $\vec{p}_0$, then this expression according to (2) is identically **0**.

Weighting

Depending on the basic shape of the intensity distribution in a pupil surface (for example circular disc-shaped, ring-shaped or arrangement of a plurality of poles), it may be expedient for certain illumination parameters to be taken into account differently in the minimisation described above. If one of the illumination parameters is for example the pupil ellipticity already explained above with the aid of FIG. **3**, then this quantity makes little sense for dipole illuminations. This illumination parameter in dipole illumination could therefore be reduced in its weighting or even remain entirely neglected by a weighting factor of 0.

If the illumination parameters $p_1, \ldots, p_m$ are weighted with weighting factors $w_1, \ldots w_m$, then the expression to be minimised becomes

$$\|w^T = (\vec{x} \cdot \overleftrightarrow{S} - \vec{p})\| \tag{3}$$

where the vector $\vec{w}$ has the weighting factors $w_1, \ldots, w_m$ as components. Further details regarding the dependency of the weighting factors $w_1, \ldots, w_m$ on the basic illumination shape may be found below in section 6.3.

Properties of the mask **14** to be illuminated may moreover also be taken into account by the weighting factors $w_1, \ldots, w_m$. In the case of a mask which only contains structures extending along one structure direction, certain illumination parameters, for example the pupil ellipticity, may be irrelevant for the image finally obtained on the photosensitive layer **22**. More serious degradations of such illumination parameters may therefore be tolerated so as to improve other illumination parameters in return.

The dependency of the weighting factors $w_1, \ldots, w_m$ on the mask may in this case be specified so that different sets $\vec{w}$ of weighting factors $w_1, \ldots, w_m$ are assigned to particular mask types. For imaging a mask to be imaged, the operator of the projection exposure apparatus **10** will then select a mask type which most closely resembles the mask to be imaged, and select the set $\vec{w}$ of weighting factors $w_1, \ldots, w_m$ which is assigned to this mask type. Deliberate adaptation of the weighting factors to different mask type therefore leads not necessarily to an overall "better" approximation of the actual illumination parameters to the target parameters according to Equation (2), but rather to a kind of "redistribution" of the deviations so that they can be tolerated better.

Adaptation of the weighting factors to a mask to be imaged may, however, be carried out specifically for individual situations by the operator of the projection exposure apparatus **10**. In this case the mask is not (only) assigned to a particular mask type, rather the weighting factors are determined in a way which is tailored directly to the mask to be imaged. Here, the operator thus does not influence the manipulators M**1** to M**7** directly by specifying control commands, but instead influences merely the weighting factors $w_1, \ldots, w_m$ for the individual illumination parameters. From this the computer **80** of the control unit **78** calculates control commands for the manipulators M**1** to M**7**, which contribute to best possible imaging of the mask.

The weighting factors may also be determined by taking into account the imaging properties of the projection objective **20** which images the mask **14**. For example, certain projection objectives may react particularly sensitively to telecentricity errors, for which reason illumination parameters that directly or indirectly relate to telecentricity errors should correspondingly be weighted more highly.

Very generally, it is preferable for the operator of the projection exposure apparatus **10** to have the opportunity to be able to determine the weighting factors freely in the control unit **78** of the illumination system **12**, at least within certain limits. It is then also possible to take into account quantities and influences other than those mentioned above from the overall imaging process.

Improvement by Iterative Readjustment

The linear relationship assumed in equation Eq. (1) between the control commands $\vec{x}$ and the illumination parameters $\vec{p}$ is satisfied only approximately for real illumination systems **12**. Inaccuracies may furthermore arise when determining the sensitivity matrix $\overleftrightarrow{S}$, owing to measurement errors etc.

In order to reduce these error sources, the control commands $\vec{x}$, which have been obtained by minimising the expression specified in (3), may be subjected to a subsequent check by measurement techniques. To this end, the manipulators M**1** to M**7** are driven with the control commands $\vec{x}$. In the event that there are intolerable deviations of the illumination parameters $\vec{p}$ obtained from the measured illumination angle distribution, from the target illumination parameters $\vec{p}_0$, the manipulators M**1** to M**7** will be readjusted. This process is repeated until the control commands $\vec{x}$ practically no longer change, i.e. they satisfy a threshold value criterion or a sign change criterion. Such an iterative method ensures that the control commands are modified until measurements reveal that the illumination parameters $\vec{p}$ have approximated the target illumination parameters $\vec{p}_0$ as closely as possible in the sense of the minimisation criteria specified in (2) or (3).

(f) Applying the Control Commands

In a step S**6** the control commands determined in step S**5** are applied to the optical elements, or to the manipulators M**1** to M**7** used for adjusting them. According to the adjustment algorithm used in step S**5**, the manipulators M**1** to M**7** are driven so that the illumination angle distribution actually achieved is as similar as possible to the target illumination distribution defined by the target illumination parameters.

(g) Illuminating the Mask

With the illumination angle distribution set up in this way, the mask **14** is finally illuminated in a step S**7** and imaged onto the photosensitive layer **22**.

It is to be understood that the sequence of the steps S**1** to S**7** as indicated above is not mandatory. In particular, the steps S**1** to S**4** may be interchanged with one another in any desired way.

6. Variants of the Method

Further exemplary embodiments of an adjustment algorithm will be described below as variants of the method explained above with the aid of FIGS. **4** and **5**.

6.1 Field Dependencies

FIG. **6** shows essential quantities of the adjustment algorithm in a representation derived from FIG. **5**, according to a variant in which it is assumed that the illumination parameters $\vec{p}$ are not constant inside the illumination field **16** illuminated on the mask **14**, but instead vary locally. Such a variation, also referred to as field dependency, may be taken into account by having the individual illumination parameters depend on the field coordinates i.e. the position on the mask **14**, i.e. $\vec{p}=\vec{p}(x, y)$ where (x, y) are the coordinates of a field point in the mask plane **58**. The functional dependency of the illumination parameters on the field coordinates may, for example, be approximated by a polynomial expansion. The minimisation of the expressions (2) or (3), performed in step S**5**, is then preferably carried out so that an equally good approximation to the target illumination parameters is obtained on average for all field coordinates. In the event that for certain masks, for instance, some regions on the mask react less sensitively to deviations from the target illumination parameters, individual regions on the mask may also be weighted by additional weighting factors.

6.2 Setting Dependency of the Sensitivities

With certain models for describing the illumination angle distribution, it may be expedient to determine the sensitivity matrix $\overleftrightarrow{S}$ separately for different basic shapes of the intensity distribution in a pupil surface. For example, it is feasible to distinguish between circular disc-shaped, ring-shaped and multi-pole basic shapes and to determine separate sensitivity matrices $\overleftrightarrow{S}_{BS}$ for these basic shapes.

6.3 Setting Dependency of the Weighting Factors

If the manipulators M**1** to M**7** can be adjusted when changing the basic illumination shape, then in the exemplary embodiment explained with the aid of the diagram in FIG. **6** not only the sensitivity matrix $\overleftrightarrow{S}_{BS}$ adapted to this basic shape, but also a weighting vector $\vec{w}_{SB}$ which has likewise been specially determined for this basic illumination shape, will be used for the minimisation of the expression (3). Optimal driving of the manipulators M**1** to M**7** is thereby achieved for each basic illumination shape.

The number of basic illumination shapes, for which a sensitivity matrix $\overleftrightarrow{S}_{BS}$ adapted thereto and weighting factors $\vec{w}_{SB}$ adapted thereto can be determined beforehand, is limited. Precisely with new types of target illumination angle distributions, the desire may therefore arise to determine sensitivities and weighting factors for the eventuality that the target illumination angle distribution does not correspond to any of the basic illumination shapes for which sensitivity matrices $\overleftrightarrow{S}_{BS}$ adapted thereto and weighting factors adapted thereto have been found.

The simplest solution in this situation consists in selecting that basic illumination shape which corresponds most closely to the target illumination angle distribution. As an alternative to this, basic illumination shapes as well as the sensitivity matrices $\overleftrightarrow{S}_{BS}$ and weighting factors $\vec{w}_{SB}$ found for them may be interpolated. In this case that sensitivity matrix $\vec{S}_{BS}$ and those weighting factors $\vec{w}_{SB}$, which correspond to an interpolated basic shape that corresponds most closely to the desired target illumination angle distribution, will be used in the adjustment algorithm.

6.4 Vector Zernike Pupil Model

A special pupil model will be presented below which is particularly highly suitable for describing intensity distributions of light bundles, assigned to individual field points, in an exit pupil. As may be seen in the diagram of FIG. **7**, the sensitivity matrix $\vec{S}$ in this pupil model may be independent of the selected basic illumination shape. This is an important advantage in so far as determining sensitivities for different basic illumination shapes is very computer-intensive in the case of simulation, and very time-consuming in the case of measurement. When this pupil model is employed, the basic illumination shape then affects only the weighting factors $\vec{w}$.

In order to explain the pupil model referred to below as the vector Zernike model, reference will first be made to FIG. **8**. This shows the geometrical relationships between a surface, referred to here as a generalised pupil EP, and the mask plane **58**. The generalised pupil concept is used in particular when the exit pupil of an optical system lies at infinity, as is the case with telecentric field diaphragm objectives **56**. In order to avoid having to deal with quantities lying at infinity, the physical conditions in the exit pupil are described in the generalised pupil. This is a kind of substitute pupil, which is geometrically similar to the exit pupil but has a finite radius and lies in the image space. Since the angles arising in the generalised pupil coincide with those in the exit pupil, for problems in which it is only the angles occurring that are important, the physical conditions in the exit pupil may be described equally well in the generalised pupil. The generalised pupil concept is explained in more detail in an article by C. W. McCutchen entitled "*Generalized aperture and the three-dimensional diffraction image*", Journal of the Optical Society of America, volume 54 (1964), pages 240-244.

Field diaphragm objectives of illumination systems of microlithographic projection exposure apparatus satisfy the sine condition with high accuracy. The generalised pupil EP for a particular image point therefore has the shape of a sphere surface, at the centre of which the relevant field point in the illumination field **16** lies. Although the exit pupil will still be referred to below for the sake of simplicity, the mathematical description does however refer to the generalised pupil EP.

The electromagnetic field in the exit pupil will be regarded approximately as purely transverse, so that the electric field vector $\vec{E}_{3D}$ is perpendicular to the bundle direction. In general, however, it is sufficient for the vector of the electric field strength $\vec{E}$ to be considered merely as a two-dimensional quantity which has the following form:

$$\vec{E}(p,q) = \begin{pmatrix} \tilde{E}_x(p,q) \\ \tilde{E}_y(p,q) \end{pmatrix}. \qquad (4)$$

Here, $\tilde{E}_x$ and $\tilde{E}_y$ denote the complex components of the electric field strength $\vec{E}$. Dimensionless pupil coordinates for positions $\vec{\sigma}$ in the exit pupil are denoted by p, q:

$$\vec{\sigma} = \begin{pmatrix} p \\ q \end{pmatrix}. \qquad (5)$$

The pupil coordinates p, q are related to the propagation angles in the image space as follows:

$$p = n \sin\Theta \cos\phi$$

$$q = n \sin\Theta \sin\phi \qquad (6)$$

The refractive index of the medium, which fills the image space in and immediately before the mask plane **58**, is denoted here by n.

With $k_0 = 2\pi/\lambda_0$, the propagation vector of a plane wave at the pupil point $\vec{\sigma}$ then reads

$$\vec{k} = k_o \begin{pmatrix} p \\ q \\ m \end{pmatrix}, \qquad (7)$$

where

$$m = \sqrt{n^2 - p^2 - q^2} \qquad (8)$$

Let an ideal intensity P_0 at the pupil position $\vec{\sigma}$ for a target intensity distribution in the exit pupil be given by $P_0(\vec{\sigma})$. In the pupil model described here, a perturbation of the illumination angle distribution is characterised by two functions $\vec{T}(\vec{\sigma})$ and $M(\vec{\sigma})$. The function $\vec{T}(\vec{\sigma})$ represents a coordinate transformation, which may be regarded intuitively as a distortion, and the function $M(\vec{\sigma})$ describes an additional intensity modulation of the exit pupil. The real (perturbed) intensity distribution $P(\vec{\sigma})$ in the exit pupil can then be represented as

$$P(\vec{\sigma}) = M(\vec{\sigma}) \cdot \frac{1}{\det\left(\partial \vec{T} / \partial \vec{\sigma}\right)} \cdot P_0\left(\vec{T}(\vec{\sigma})\right)$$

or more simply as (9)

$$P(\vec{\sigma}) = M'(\vec{\sigma}) \cdot P_0(\vec{T}(\vec{\sigma})),$$

if the scalar normalisation $1/\det(\partial\vec{T}/\partial\vec{\sigma})$ is combined with the function $M(\vec{\sigma})$.

Both the vector function $\vec{T}(\vec{\sigma})$ and the scalar function $M(\vec{\sigma})$ are now approximated as a superposition of functions of a complete, preferably orthogonal system of basis function. The function $M(\vec{\sigma})$ may, for example, be approximated by a sum of Zernike polynomials in the form

$$M(\vec{\sigma}) = 1 + \sum_{k=1}^{\infty} \alpha_k \cdot U_k(\vec{\sigma}), \qquad (10)$$

where $U_k(\vec{\sigma})$ are the conventional Zernike polynomials.

The coordinate transformation $\vec{T}(\vec{\sigma})$ may be parameterised by the following vector Zernike decomposition:

$$\vec{T}(\vec{\sigma}) = \vec{\sigma} + \sum_{k=-\infty,k\neq 0}^{\infty} \beta_k \cdot \vec{W}_k(\vec{\sigma}). \tag{11}$$

The vector Zernike polynomials $\vec{W}_k(\vec{\sigma})$ are given by

$$\vec{W}_k(\vec{\sigma}) = R_n^{\ m} \vec{\Phi}_{m\epsilon}, \tag{12}$$

where $R_n^{\ m}$ is the radial component of a kth order Zernike polynomial, $\vec{\Phi}_{m\epsilon}$ is given by

$$\vec{\Phi}_{m\varepsilon} = \begin{pmatrix} \cos(\varepsilon\pi/2) & -\sin(\varepsilon\pi/2) \\ \sin(\varepsilon\pi/2) & \cos(\varepsilon\pi/2) \end{pmatrix} \begin{pmatrix} \cos m\varphi \\ -\sin m\varphi \end{pmatrix} \tag{13}$$

and the order number k is linked to n, m and ϵ through the following table

k	1	−1	2	−2	3	−3	4	−4	5	−5	6	−6
n	0	0	1	1	1	1	2	2	2	2	2	2
m	0	0	1	1	−1	−1	0	0	2	2	−2	−2
ϵ	0	1	0	1	0	1	0	1	0	1	0	1

etc.

The vector Zernike polynomials with the order numbers 1 to 8 and −1 to −8 are graphically represented in FIGS. **9***a* to **9***h* and **10***a* to **10***h*, respectively. The terms "1" and "−1" correspond to a geometrical x or y telecentricity, and the terms "2" and "−2" represent a geometrical HV or ST ellipse. The term "3" corresponds to an enlargement of the pupil, "−3" corresponds to a rotation of the pupil etc.

Since the basis functions, on which the two decompositions according to Eqs (10) and (11) are based, form a complete function system, any desired real intensity distribution in an exit pupil assigned to a particular field point can be described by specifying an (arbitrary) ideal intensity distribution $P_0(\vec{\sigma})$ and the superposition coefficients α_k and β_k, the superposition coefficients α_k and β_k describing the perturbation with respect to the ideal intensity distribution $P_0(\vec{\sigma})$. It is in this case unimportant whether the real intensity distribution $P(\vec{\sigma})$ itself is described by another parametric model or by a sufficiently large number of measurement values. In both cases, the superposition coefficients α_k and β_k represent illumination parameters which can be used according to the method described in section 5 to determine control commands for the manipulators M**1** to M**7**, so that the intensity distribution actually obtained in the exit pupil resembles the desired target intensity distribution as closely as possible.

Since any desired intensity distributions in exit pupils can be described by the vector Zernike pupil model with an accuracy which in the end is freely selectable, it is actually sufficient to determine the sensitivity matrix $\ddot{S}$ only once for the basis functions assigned to the superposition coefficients α_k and β_k. Similarly as described above in **5**(*c*), to this end for example it is possible to measure how the adjustment of an optical element, generated by a manipulator, affects the various basis functions. A sensitivity matrix $\ddot{S}$ obtained in this way can then be used for any desired basic illumination shape. This obviates the outlay on determining the sensitivity matrices for different basic illumination shapes.

Another advantage of using the vector Zernike pupil model is that the description of the intensity distribution in the exit pupil, as a perturbation of an ideal intensity distribution, makes it possible to give the individual superposition coefficients α_k and β_k a meaning which is immediately intuitive in many cases. The superposition coefficients α_k and β_k can therefore be employed not only in conjunction with the driving of the manipulators M**1** to M**7**, but also very generally for evaluating illumination angle distributions. If, for example, a calculation for a particular illumination system **12** and a diffractive optical element **36** reveal that the superposition coefficient α_{-3} is significantly different from zero in a dipole illumination, then this can be interpreted intuitively as a rotation of the two poles about the optical axis.

Such an evaluation may also be used advantageously for producing illumination systems. For example a quality function may be established, to which at least one of the superposition coefficients contributes. Starting from an original design for the illumination system, the design may then be modified until the quality function is improved or until no further improvement takes place.

By additional adjustment steps after production and before delivery, an illumination system may be improved further in respect of the illumination angle distributions which can be set up. To this end, the illumination angle distribution may initially be evaluated in the manner indicated. By adjustment steps, for example slight translational displacement or tilting of particular optical elements, the illumination angle distribution may then be modified so that the evaluation is improved.

In the finished illumination system, the superposition coefficients α_k and β_k may for example be used to make predictions for new basic illumination shapes in the scope of simulations. The fact that many of the superposition coefficients α_k and β_k have an intuitive meaning then significantly facilitates the work of the developer who is carrying out the simulation.

Owing to the possibility of specifying weighting factors for the individual illumination parameters (i.e. the superposition coefficients α_k and β_k), here again the illumination system **12** overall may be optimised in the form of a "compromise" between a large number of different basic illumination shapes and mask types. As an alternative to this, it is possible to specify different weighting factors as a function of the basic illumination shape. Furthermore, if desired, the weighting factors may also be determined here as a function of the mask **14** to be imaged.

Instead of the decompositions specified in Eqs (10) and (11), decompositions may also be carried out based on other complete, preferably orthogonal systems of basis functions. For the function $\vec{T}(\vec{\sigma})$, for example, a decomposition into vector modes according to

$$\vec{T}(\vec{\sigma}) \approx \vec{\sigma} + \sum_{j=-N}^{N} \tilde{Z}_j \vec{V}_j(\vec{\sigma}), \tag{14}$$

may be envisaged. The vector modes $\vec{V}_j(\vec{\sigma})$ are in this case given by

$$\vec{V}_{+j} = \begin{pmatrix} U_j(\vec{\sigma}) \\ 0 \end{pmatrix}, \vec{V}_{-j} = \begin{pmatrix} 0 \\ U_j(\vec{\sigma}) \end{pmatrix} \tag{15}$$

where $\vec{V}_{+j}$ is a vector mode for positive j, $\vec{V}_{+j}$ is a vector mode for negative j and $U_j(\vec{\sigma})$ are again the conventional j^{th} order Zernike polynomials.

Methods, with which the superposition coefficients α_k and β_k can be determined by measurement techniques, will be described below:

6.4.1 Fitting

In this method different basic illumination shapes, the idealised intensity distribution $P_0(\vec{\sigma})$ of which is known, are set up in the illumination system **12**. For each basic illumination shape, the actual intensity distribution in the exit pupil is measured. Now, for each basic illumination shape, the superposition coefficients α_k and β_k can be determined by fitting. It will be noted that the ideal intensity distribution $P_0(\vec{\sigma})$, which goes into Eq. (9), always stays the same and may for example correspond to one of the basic illumination shapes, although it does not have to.

Repetition of the measurement and fitting steps for different basic illumination shapes is desirable because certain superposition coefficients occur only in selected basic illumination shapes. For instance the rotation shown in FIG. **10***c*, which is described by the superposition coefficients β_{-3}, is not measurable in rotationally symmetric basic illumination shapes although certain manipulators M**1** to M**7** may possibly generate such a rotation. Only when a non-rotationally symmetric basic illumination shape is set up can the superposition coefficient β_{-3} be determined.

Since the number of basic illumination shapes which can be measured is limited, in principle it is actually possible to determine only a subset of the superposition coefficients α_k and β_k. Above all for new types of basic illumination shapes which differ significantly from the measured basic illumination shapes, it is therefore only limitedly possible to draw conclusions about the actual illumination angle distribution which can be set up in the mask plane **58** by the manipulators M**1** to M**7**.

6.4.2 Use of a Grating

In this method the diffractive optical element **36** is replaced by a diffraction grating, which is constructed particularly simply but owing to its simplicity can be manufactured very accurately. During manufacture, for example, a chromium layer which has been vapour deposited on a support material may be structured with the aid of lithographic methods. The position of the diffraction orders of the grating in the exit pupil and the relative intensity of the individual diffraction orders can be predicted very accurately with the aid of simulations.

If the intensity distribution in the exit pupil is now measured for one or more field points, then the superposition coefficients β_k can be determined from the actual position of the diffraction orders while the relative intensity of the diffraction orders, compared with the theoretically expected values, gives the superposition coefficients α_k.

This method may be employed similarly in an illumination system which adjusts the illumination angle distribution via a diaphragm arranged in a pupil surface. Only the sections of the diffraction orders which are let through by the diaphragm then appear in the exit pupil.

In contrast to the method described in 6.4.1, in principle all the superposition coefficients α_k and β_k can be determined

with the aid of such a grating. It is therefore possible to predict better how an illumination system **12** will react to entirely new combinations of control commands, and including those combinations of control commands which correspond to entirely new types of basic illumination shapes which were not known when configuring the illumination system **12**.

6.5 Adaptation of the Mask

Under certain circumstances, the desired illumination angle distribution may not be achieved in the mask plane **58** despite optimal adjustment of the manipulators M**1** to M**7**. Reasons for this may inter alia be undesired field dependencies of the superposition coefficients α_k and β_k, for which in general there are no possibilities of correction.

Describing the intensity distribution in the exit pupil with the aid of the vector Zernike pupil model, however, allows the uncorrectable deviations from the ideal illumination angle distribution to be taken into account when configuring the mask **14**. In the case of a field-dependent illumination angle distribution, this may for example be done by structures of the same type on the mask being position-dependently designed differently so as to compensate in some degree for the different illumination angle distributions at these positions.

What is claimed is:

1. A method for setting an intensity distribution for a pupil of an illumination system of a microlithography tool, the method comprising:

measuring an initial intensity distribution for the pupil of the illumination system;

determining variations between the initial intensity distribution and a target intensity distribution for the pupil, the variations being characterized by an intensity modulation and a distortion, the intensity modulation being expressed as a first combination of functions based on Zernike polynomials and the distortion being expressed by a second combination of functions; and

adjusting at least one element in the illumination system to reduce the variations between the initial and target intensity distributions for the pupil.

2. The method of claim **1**, wherein the initial intensity distribution is measured using a sensor.

3. The method of claim **2**, wherein the sensor is positioned at a mask plane of the illumination system or at an image plane of a projection objective in the microlithography tool.

4. The method of claim **2**, wherein the sensor is an angle-resolving sensor.

5. The method of claim **1**, wherein the target intensity distribution comprises a plurality of individual regions arranged displaced from an optical axis of the illumination system.

6. The method of claim **5**, wherein the target intensity distribution is a multipole intensity distribution.

7. The method of claim **6**, wherein the multipole intensity distribution is a dipole intensity distribution or a quadrupole intensity distribution.

8. The method of claim **1**, wherein the illumination system is arranged to illuminate a mask in the microlithography tool and the target intensity distribution is selected so that the mask is only illuminated obliquely.

9. The method of claim **1**, wherein the illumination system is arranged to illuminate a mask in the microlithography tool and the target intensity distribution is selected to illuminate the mask optimally based on properties of the mask.

10. The method of claim **1**, wherein the first and second combinations of functions are functions of orthogonal pupil coordinates.

11. The method of claim **1**, wherein the second combination of functions characterizing the distortion corresponds to a coordinate transformation of the initial intensity distribution.

12. The method of claim **11**, wherein the variation corresponds to a product of the first combination of functions characterizing the intensity modulation and the target intensity distribution transformed by the coordinate transformation.

13. The method of claim **1**, wherein the first combination of functions characterizing the intensity modulation is expressed as a scalar function.

14. The method of claim **1**, wherein first combination of functions is a linear combination of functions.

15. The method of claim **1**, wherein the second combination of functions characterizing the distortion is expressed as a vector function.

16. The method of claim **1**, wherein the second combination of functions is a linear combination of functions.

17. The method of claim **1**, wherein the second combination of functions comprise Zernike functions.

18. The method of claim **1**, wherein the at least one element is adjusted in response to a control command generated based on the determined variations.

19. The method of claim **18**, wherein the at least one element is adjusted using a manipulator which receives the control command.

20. The method of claim **19**, wherein the control command is generated by a computer based on the determined variation, the computer being in communication with the manipulator.

21. The method of claim **1**, further comprising illuminating a mask using the illumination system after the at least one element is adjusted.

22. The method of claim **1**, wherein the illumination system comprises an adjustable mirror arrangement.

23. The method of claim **22**, wherein the adjustable mirror arrangement is configured to increase the dimensions of a light bundle emitted by a light source.

24. The method of claim **23**, wherein the light source is an excimer laser.

25. The method of claim **22**, wherein the illumination system is arranged to illuminate a rectangular or ring segment shaped field at the mask.

26. The method of claim **22**, wherein the illumination system further comprises an optical integrator arranged in or in the immediate vicinity of the pupil plane.

27. The method of claim **1**, wherein the at least one element is selected from the group consisting of a diffractive optical element, a zoom objective, and a pair of axicon elements.

28. A microlithography tool, comprising:

an illumination system arranged to direct light from a light source to a mask plane during operation of the microlithography tool, the illumination system defining an intensity distribution for a pupil of the illumination system and comprising at least one element coupled to a manipulator;

a projection objective arranged to image structures on a mask positioned at the mask plane to an image plane during operation of the microlithography tool;

a sensor configured to measure an initial intensity distribution for the pupil of the illumination system; and

a computer in communication with the sensor and the manipulator, the computer being programmed to determine variations between the initial intensity distribution and a target intensity distribution for the pupil, the variations being characterized by an intensity modulation and a distortion, the intensity modulation being expressed as a first combination of functions based on Zernike polynomials and the distortion being expressed by a second combination of functions,

the computer being further programmed to cause the manipulator to adjust the at least one element to reduce variations between the initial and target intensity distributions for the pupil.

29. The microlithography tool of claim **28**, wherein the illumination system comprises an adjustable mirror arrangement.

30. The microlithography tool of claim **28**, wherein the sensor is positioned at the mask plane of the illumination system or at the image plane of the projection objective.

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